ADVANCED TRANSPARENT POLYMER DEVELOPMENT FOR LIGHTWEIGHT TRANSPARENT ARMOR (U)

Richard A. Huyett
Armor Technology Specialist
Simula Technologies, Inc.
Phoenix, Arizona 85044

ABSTRACT (U)

(U) This paper describes a family of new transparent polyurethane polymers developed by Simula Technologies, Inc.. The new polymers possess improved properties which can significantly reduce the weight of transparent armor used for protection against small-arms projectile, ballistic fragmentation, and laser threats, either singly or in combination. The key properties of the new polymers are presented and compared to currently used materials, such as as-cast acrylic and polycarbonate. The polymer's unique processing characteristics, which facilitate the manufacture of configured eye protection devices and transparent armor for ground vehicles and aircraft, are also discussed.

(U) The contributions which the new polymers have made to date to several key U.S. Army advanced transparent armor development programs are described. The polymer's planned use within the Army's newly-awarded Advanced Lightweight Transparent Armor program are also presented. A number of design architectures are shown which illustrate the breadth of the polymer's potential usage, both as individual components and as complete transparent armor systems. In addition to weight savings, the polymer's processing characteristics and properties offer the promise of reduced manufacturing costs and improved durability in service.

(U) <u>Introduction</u>

(U) Several of the U.S. Army's major thrust programs seek to reduce the weight of transparent armor. The scope of the Army's search for reduced weight solutions for transparent armor runs from individually worn eye protection devices, such as spectacle lenses and visors, to glass/plastic laminates for aircraft and ground vehicles transparencies which are capable of defeating high-velocity small-arms projectiles and ballistic fragments.

(U) The performance of transparent armor has historically lagged behind that of opaque armor, when judged by the armor's mass-efficiency parameter. The mass-efficiency parameter is the comparative ratio of the transparent armor's areal density to the areal density of a standard armor material, usually steel or aluminum plate, that is required to defeat the same threat under nominally identical test conditions. The highest-performing transparent armor designed to defeat small-arms projectiles typically consists of a laminated glass / plastic composite. The hard glass striking ply is required to blunt and/or break up the pointed projectile and dissipate a substantial portion of its kinetic energy. The plastic back ply prevents the passage of spall, in the form of projectile or glass fragments, while it dissipates the remaining kinetic energy.

(U) The most efficient designs of transparent armor intended to defeat fragmentation from explosive ordnance have traditionally been monolithic or laminated plastic(s). Glass, due to its high density, is historically not competitive in defeating the irregularly shaped, and less-penetrating, fragment threats.

(U) The state of the art in transparent armor has been unchanged for many years, due to the lack of higher-performance component materials such as transparent ceramics, glass / ceramics, glass, and plastics. No new plastic has been commercialized for use in the volume manufacture of transparent armor since polycarbonate was introduced into the market in 1958.

(U) Simula Technologies, Inc., (Simula) is developing a new family of transparent polyurethane polymers which have an unusual combination of properties. Several of these polymers, even in their early stages of development, show great promise for improving the performance of many types of transparent armor.

(U) Simula has recently performed several Government-funded research and development programs relating to transparent armor concepts for personal eye protection devices, helicopter armor, and the optimization of transparent armor designs using computational modeling. The results of this work show that it is now possible to create armor designs affording substantially higher protection or reduced weight by incorporating new, higher-performance transparent polymers.

(U) Background

(U) Simula's polymer development work was initiated as a company-funded research and development program which was conducted during 1993. At that time, Simula was performing the Helicopter Advanced Armor Concepts (HAAC) Program (Reference 1), for the U.S. Army Aviation and Troop Command, Aviation Applied Technology Directorate (AATD), Fort Eustis, Virginia. The purpose of this program was to develop and define weight-saving advanced armor concepts, both opaque and transparent, for helicopter applications.

(U) Simula recognized the potential for improvements in the ballistic performance of transparent armor which could result from a polymer formulated specifically for armor usage. A program was begun to accomplish this task. Using newly available component materials and innovative chemistries, a family of new transparent polyurethane polymers was created. The first polymer of merit, S-1180, was incorporated into the final HAAC program blast / fragmentation barrier design samples delivered to the Government for testing. The Government-conducted live-fire testing using 23-mm high-explosive incendiary (HEI) ordnance demonstrated that the design offered the potential of meeting the program's ballistic performance goal at an areal density 20.4 pct lower than the program baseline in lieu of the 10 pct reduction program goal.

(U) Simula's ongoing work has, to date, resulted in a family of thermoset and thermoplastic polymers which far exceed the properties and performance attained with S-1180. The identification codes, physical, mechanical, optical, and ballistic properties for the currently best-performing polymers will be presented later.

(U) New Polymer Properties

(U) The best-performing polymer developed and characterized to date is SIM 2003, which is also known as Cleargard™. The properties of SIM 2003 are shown in Table I. The properties of as-cast acrylic and polycarbonate are included for comparative purposes. The superior properties of the new polymer has expanded the scope of the materials' potential product applications well beyond the original program goals.

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Table I. (U) Comparative polymers properties data

Property	Units	As-Cast Acrylic	Polycarbonate	SIM 2003
Color	-	Water Clear	Water clear, Light gray, or Light straw	Near water clear
Yellowness Index	-	-	1.00	2.00
Specific Gravity	-	1.20	1.20	1.14
Hardness	D Scale	92-93	84-86	80-81
Fischer Microhardness	N/mm^2	184	116	62.6
Luminous Transmittance	Pct	91	89	93
Haze	Pct	1.0	0.6-1.0	0.5
Refractive Index	-	1.490	1.586	1.538
Abbe No.	-	-	27.0	40.0
Heat Deflection Temperature (254 $lb/in.^2$)	^oF	212	276	300
Stress Craze Resistance (isopropyl alcohol)	$lb/in.^2$	3,800	4,000	>7,000
Tensile Strength - Ultimate	$lb/in.^2$	10,500	9,500	7,326
Elongation	Pct	4-5	80	286
Modulus	$lb/in.^2$	450,000	340,000	118,000

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(U) SIM 2003 has exceptional toughness combined with very attractive optical properties. As is shown in Figure 1, SIM 2003 provides substantially higher ballistic performance than polycarbonate or as-cast acrylic. These data were obtained using MIL-P-46593A fragment-simulating projectiles (FSP's). The

™ Cleargard is a trademark of Simula, Inc. (U) family of MIL-P-46593A FSP's were developed by the Government for use as simulants for the fragments produced by various types of explosive ordnance (See Figure 2). Their use in laboratory ballistic testing facilitates the generation of comparative data for competing armor systems.

(U) It is informative to note that 0.125-in.-thick SIM 2003 provides the same V_{50} PBL as does the 0.25-in.-thick polycarbonate. However, the polycarbonate data shown in Figure 1 is comparatively overstated for most eye protection devices. The data was obtained by testing polycarbonate in extruded sheet form, which has higher ballistic performance than the grades of polycarbonate which are injection-molded into optical devices such as visors and lenses.

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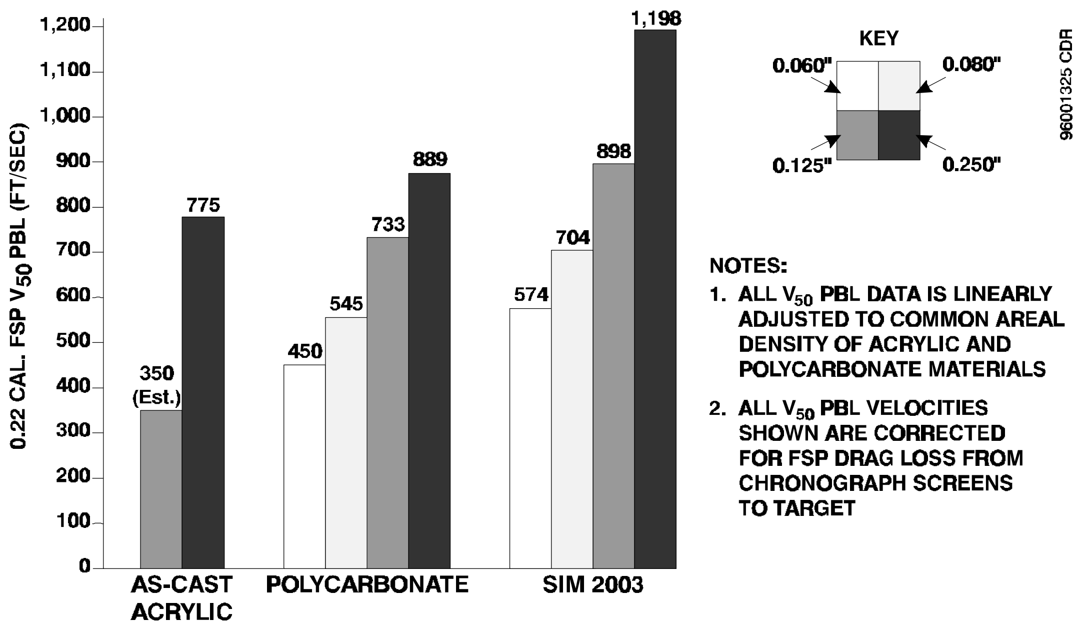

Figure 1. (U) Comparative polymer ballistic test data.

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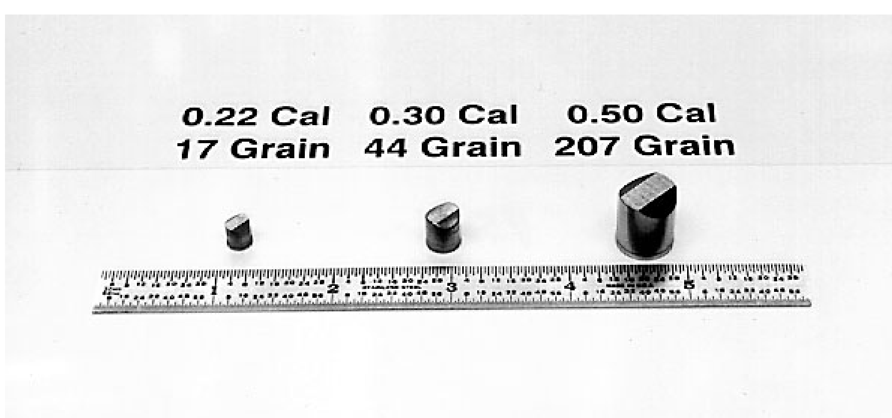

Figure 2. (U) Fragment-simulating projectiles per MIL-P-46593A.

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(U) The SIM 2003 polymer's lack of color, high luminous transmittance, and very low haze characteristics support its use in critical optical applications such as helmet visors, face shields, goggle lenses, spectacle lenses, and aircraft transparencies. SIM 2003 has chemical resistance, abrasion resistance, and thermal resistance properties that far exceed those of polycarbonate. SIM 2003 also has a specific gravity of 1.14, which is 5.0 pct less than acrylic and polycarbonate, and 13.0 pct less than allyl diglycol carbonate.

(U) The chemistry of SIM 2003 offers broad formulation freedom and very tailorable processing characteristics. These attributes facilitate adjusting properties to meet specific application requirements, and attaining an economical manufacturing process. The chemistry of SIM 2003 is compatible with many specialty additives such as melanin, which is a natural skin pigment now being employed as an advanced ultraviolet radiation blocker for eye protection.

(U) Simula Technologies' Polymer's Contributions to Advanced Armor Development Programs

(U) In addition to the previously mentioned HAAC program, Simula's new polymers have benefited several other advanced development programs in diverse fields as follows:

(U) Transparent Armor Technology Development Using Computational Modeling Program

(U) Simula performed the Transparent Armor Technology Development Using Computational Modeling Program for the Advanced Research Projects Agency (Reference 2). This program was technically monitored by the U.S. Army Tank Automotive Command, located in Warren, Michigan. Simula's work, supported by Sandia National Laboratories (SNL) and Los Alamos National Laboratory (LANL), further developed advanced shock physics codes during the analysis of state-of-the-art designs. The improved hydrocodes were then applied by SNL and LANL to create new lighter-weight armor designs. Simula's S-1180 and SIM 2003 polymers were included in the program, together with commercial glass and polycarbonate materials.

(U) Simula's fabrication and ballistic testing of the model-generated designs showed the SNL CTH hydrocode modeling of both monolithic- and laminated-polymer-based designs to be highly predictive of the armor's empirical ballistic performance. The LANL modeling of the glass / plastic armor designs using their MESA2D and SPHINX hydrocodes to computationally predict the ballistic performance of new designs was less successful.

(U) Enhanced Dyes For Laser Eye Protection Program

(U) Simula's SIM 2003, and a highly cross-linked thermoset polyurethane, SIM 1802,were recently evaluated within the Anteon Corporation's Enhanced Dyes for Laser Eye Protection Program performed for the U.S. Air Force (Reference 3). The new polymers offer the ability to incorporate laser-absorptive dyes (both current-production and newly synthesized dyes) directly into a liquid component of the polymer prior to compounding. This solubility feature ensures homogeneity of the dye dispersal. The tailorability of the polymer cure temperature enables the use of certain high-performance dyes that are normally destroyed by the high temperatures imposed during the injection molding of polycarbonate optical devices.

(U) During the program, a total of 16 production dyes and 7 newly synthesized dyes were evaluated for compatibility and solubility with SIM 1802 and SIM 2003 polymers. Excellent results were achieved, with all 23 of the dyes being successfully incorporated into SIM 2003, and 13 of the dyes being incorporated into SIM 1802. Test coupons were delivered and optical density values were measured at each laser wavelength of interest. Much optical design work remains to be accomplished as part of a recently awarded follow-on program. Simula will work to optimize the concentration of individual dyes in the polymer host to achieve the required optical density. Subsequent work will incorporate a multi-dye recipe into the polymer which maximizes user visibility while blocking multiple wavelengths of laser radiation to an eye-safe level.

(U) <u>Advanced Lightweight Transparent Armor Program</u>

Simula was recently awarded the Advanced Lightweight Transparent Armor (ALTA) Development Program by the U.S. Army Aviation Applied Technology Directorate located in Fort Eustis, Virginia (Reference 4). The ALTA program represents a major development effort to advance the state of the art for two categories of transparent armor: glass / plastic laminate windshield armor, and plastic laminate blast / fragmentation barrier armor. The ALTA program's technically challenging goal is to further reduce the areal density of both categories of armor by 35 percent beyond the 10-percent reduction achieved in the previously described HAAC program.

(U) Simula's technical approach for the ALTA program leverages off of the higher-performing materials developed since the HAAC program ended. These improved materials come from Simula's internally funded polymer development programs, as well as from a number of outside company and academia sources identified during the conduct of the program's Task 1 - Literature Search and Armor Technology Survey.

(U) Simula has prepared and prioritized initial armor system designs incorporating various combinations of the new materials for both categories of transparent armor. Component materials have been both procured and manufactured for the prioritized designs which are scheduled to undergo the first ballistic testing. Several of the initial candidate designs are shown in Figures 3 though 6.

(U) Based upon the measured performance of the designs and the behavior of the materials contained within the designs, an iterative series of design changes to the architecture and component scaling will be determined, and then fabricated, and tested. Simula will seek to further improve the best-performing new component materials through reformulation activities conducted either in-house on Simula's polymers or conducted outside the company by the material manufacturers.

(U) The ballistic performance of the competing armor system designs will be tested in Simula's DoD-certified ballistic test facility. Deliverable samples of the best-performing design will be subjected to ballistic testing at AATD's ballistic test facility. An optional ALTA task exists which, if exercised, would involve providing selected replica windows for the AH-64 Apache attack helicopter and the C-17 Globemaster III and C-130 Hercules fixed-wing aircraft. The replica windows would incorporate the lightest-weight transparent armor which meets or exceeds the program's weight-reduction goal. The replica windshields would be non-flightworthy articles capable of undergoing testing and evaluation activities both on a stand-alone basis and after being installed on a representative aircraft.

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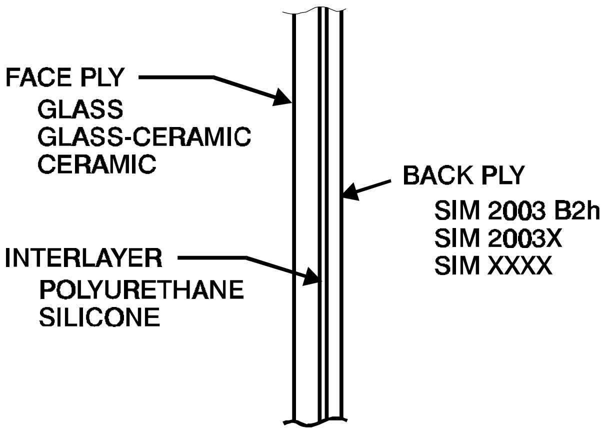

Figure 3. (U) Windshield armor.

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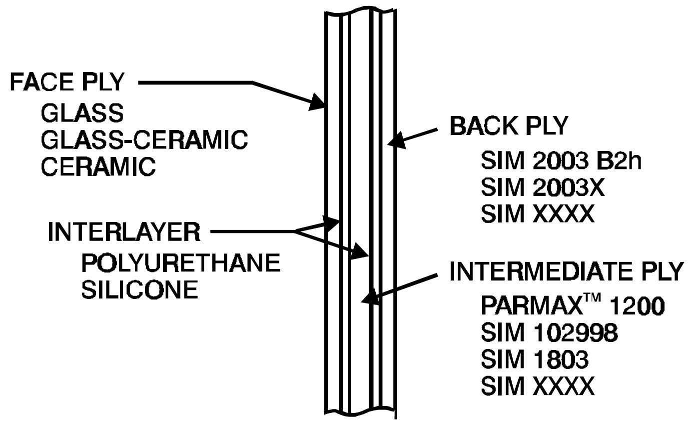

Figure 4. (U) Windshield armor.

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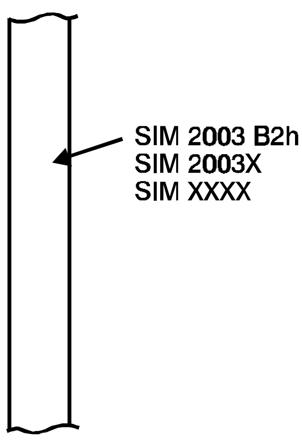

Figure 5. (U) Blast / fragmentation barrier.

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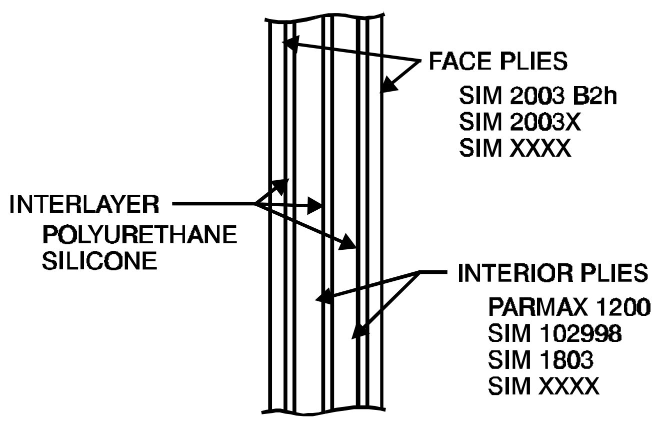

Figure 6. (U) Blast / fragmentation barrier.

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(U) Improved PASGT Helmet Visor Incorporating New Polymers

(U) The U.S. Army has expressed an interest in fielding a PASGT helmet visor which affords the same fragment protection level as the helmet body. The visors currently fielded are made of polycarbonate, and even the thickest designs fall far short of providing a 2,000-ft/sec V_{50} PBL performance against the 0.22-cal. FSP. Two new candidate visor designs for defeating the 2,000-ft/sec FSP threat are shown in Figure 7. The monolithic polymer design is preferred for simplicity, low cost, and optic quality; however, the dual-hardness design should be capable of providing the thinnest, lightest-weight possible visor capable of defeating the ballistic threat.

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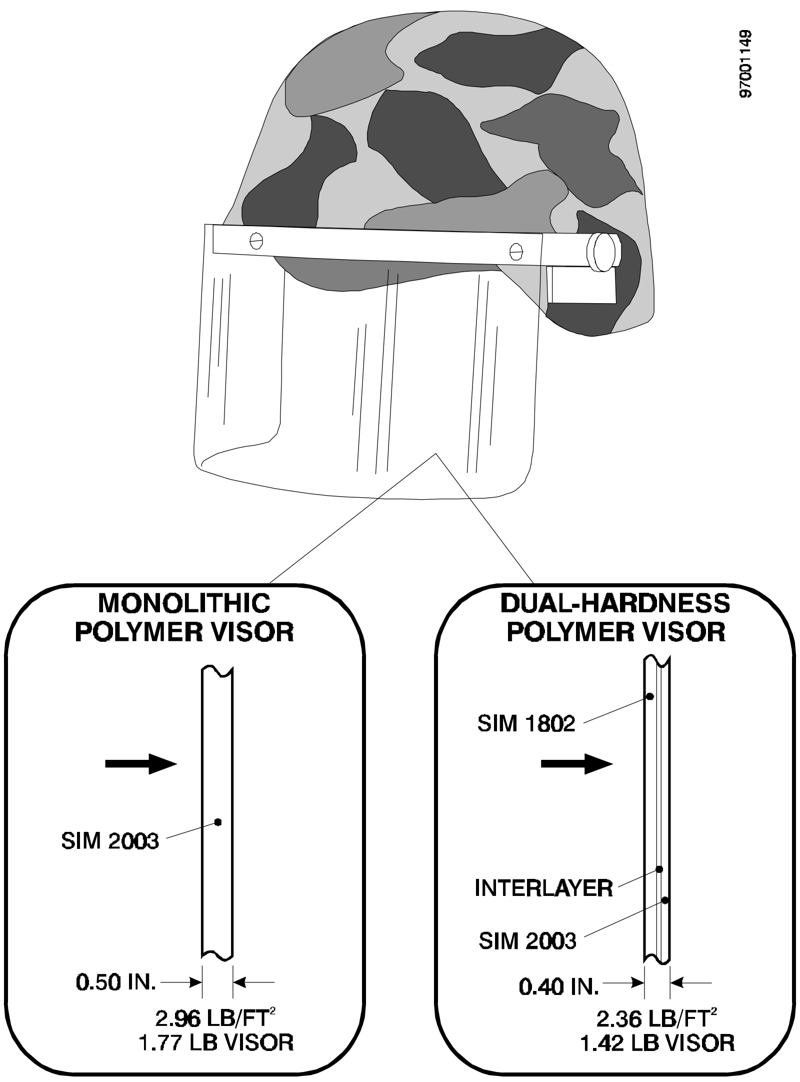

Figure 7. (U) High-performance helmet visor designs.

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(U) The new polymers are still in their development and scale-up phase, and further improvements in ballistic performance are anticipated by altering the soft-segment-versus-hard-segment of the polymer backbone, and/or by polymer alloying. These changes, if needed, combined with optimization of design architectures, offer great promise of meeting or exceeding the helmet visor weights shown in Figure 7.

(U) The high-performance polymer(s), whether monolithic or laminated, will provide very important advantages for manufacturing low-cost and robust visors for military use. The monolithic-polymer visor design can be liquid-cast to shape or formed from a flat sheet. The dual-hardness polymer visor design can be formed from a laminated flat sheet. Both the cast-to-shape and forming processes will yield excellent optical quality. The all-polymer visors will be highly break-resistant in service. The monolithic-polymer visor design eliminates the potential for in-service delamination.

(U) The optical surfaces of Simula's polymers will require a hard coating to provide a durable protective device such as a helmet visor for military use. However, the commercial hard coatings typically applied to polycarbonate work well with both the SIM 1802 and SIM 2003 polymers. Simula is also evaluating diamond-like coatings (DLC) on the new polymers to impart truly scratch-resistant protection.

(U) Glass / plastic laminate visor designs will likely not be competitive in terms of weight, manufacturing cost, and durability. A visor made to fit the PASGT helmet requires a radius of curvature of approximately 4.5 inches. Matching the shape of the glass and plastic components within the very tight tolerances required for successful lamination and acceptable optics poses a major technical challenge. It is extremely difficult to consistently form glass to such a tight radius while maintaining unmarked surfaces.

(U) A glass / plastic visor design imposes substantial risks of glass breakage and delamination. The relatively thin glass facing ply supported by a soft plastic interlayer is vulnerable to breakage due to impact with hard objects during manufacture and while in service. The delamination risk results from stress concentrations generated during lamination, residual stress in the finished laminate, and stress induced by temperature change due to the very dissimilar coefficients of thermal expansion of the glass and plastic components.

(U) Acknowledgements

(U) The author wishes to acknowledge the contributions made by the following Simula employees. Simula's polymer development work is performed under the direction of Dr. Paul Apen, the Manager of Advanced Materials Development. Edwin C. Slagel, Staff Chemist, created the S-1180, SIM 1802 and SIM 2003 transparent polymer formulations. Very significant contributions have also been made by Chemist Robert L. Fogarty in the refining and characterizing of the polymer formulations and processing techniques.

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4. (U) Contract No. DAAH10-98-C-0031, "Advanced Lightweight Transparent Armor", issued by the U.S. Army Aviation Applied Technology Directorate, Fort Eustis, Virginia.

(U) Author Biography

(U) Richard A. Huyett
Simula Technologies, Inc.
10016 South 51st Street
Phoenix, AZ 85044
Phone: 602-753-2099
Fax: 602-893-8643

(U) Mr. Richard A. Huyett holds an A.A. Degree in Mechanical Design Technology from Southern Illinois University. As a Senior Project Engineer at Simula Technologies, Inc., he conducts R&D of transparent armors including transparent polymers for protective applications. He performs mechanical, optical, and ballistic testing and evaluation on new transparent products. He is the Principal Investigator on three Simula Technologies internal R&D programs that are developing transparent polyurethane polymers. Mr. Huyett has also acted as Project Engineer on numerous Government-sponsored R&D programs relating to transparencies.

(U) Prior to joining Simula Technologies, Mr. Huyett worked at Loral Defense Systems, Arizona Division (formerly Goodyear Aerospace Corporation) as a Section Head of Transparent Products Engineering. He has 29 years of experience in the fields of transparent armor and aircraft transparencies, and has authored numerous technical reports and papers.